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Methane emissions of energy activities in China 1980–2007

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ABSTRACT

As the largest CH_4 emitter, China produces CH_4 at an increasing rate, especially from its energy activities. Presented in this paper is a detailed inventory and analysis of CH_4 emissions from energy activities in China from 1980 to 2007 covering all the significant sources. The total energy-related CH_4 emissions in China tripled during the period with an average annual increase rate of 4.7% and reached 21,943.1 Gg in 2007, 2.4 times of that in USA. As the largest emission source, coal mining increased its share from 69.2% (4559.5 Gg) in 1980 to 85.8% (18,825.5 Gg) in 2007; The second biggest source was fuel combustion, mainly bio-fuel combustion (2370.3 Gg in 2007); Oil and natural gas system leakage was a minor source but at a rapidly increasing rate. This transient emission structure is quite different from the steady structure of USA, which is dominated by the fugitive emissions from natural gas and oil systems. According to the lower IPCC Global Warming Potential, the annual energy-related CH_4 emissions were equivalent to 9.1%–11.7% of China's energy-related CO_2 emissions, amounting to 548.6 Mt CO_2-eq in 2007 which is greater than the nationwide gross CO_2 emissions in many developed countries.

Contents

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1. Introduction

Reckoned as the world's largest producer of CO_2 emissions since 2007 [1], the issue of China's GHG emissions has received much attention internationally in the context of climate change, especially with the rising pressure to reduce the emissions in the post-Kyoto negotiation [2,3]. Committed to GHG emission reduction [4], the Chinese government has set explicitly the goal to cut the CO_2 emission per unit of gross domestic product (GDP) by 40 to 45 percents by 2020 relative to the level of 2005 [5] for the development of a low carbon economy [6,7]. However, the total amount of China's GHG emissions is expected to increase further, due to the rapidly growing economy [8,9]. Extensive studies have been carried out to estimate CO_2 emissions in China and to explore the related mitigation opportunities [10–18].

In contrast to the ever-increasing focus at China's CO_2 emissions, the CH_4 emissions in China have received little attention. Methane (CH_4) as another potent greenhouse gas has a global warming potential (GWP) 72 or 25 times greater than that of carbon dioxide over a horizon of 20 or 100 years [19]. Therefore, stabilizing methane emissions as a potential policy target can dramatically contribute to greenhouse gas reduction in the near-term and to global health benefits in the long term [20–22]. Methane emissions in China are remarkably significant. According to the official GHG emission inventory of China for the year of 1994, methane by the lower GWP factor of 21 contributed 19.4% of the total nationwide GHG emissions in terms of CO_2, CH_4 and N_2O in 1994 [23]. Recently, Zhang and Chen [24] reported that the total CH_4 emissions by Chinese economy in 2007 were 39,592.7 Gg or 989.8 Mt CO_2-eq by the GWP factor of 25, with a magnitude of about one sixth of China's CO_2 emissions from fuel combustion and greater than the nationwide CO_2 emissions from fuel combustion of many developed countries such as UK, Canada, and Germany. It follows that the mere consideration of the CO_2 emissions does not reflect the real situation and full picture of China's GHG emissions [8,25].

As an important anthropogenic source for CH_4 emissions, energy activities have become the largest CH_4 emission source in China, contributing more than 40% of the total CH_4 emissions in recent years [24]. Intentional or unintentional release of CH_4 may occur during the extraction, processing and delivery of fossil fuels to the destination of final use [26]. China is the largest coal production and consumption country, large coal supply has resulted in a high growth rate of coalbed methane emissions, without an effective exploitation of coalbed methane resources [27–29]. Meanwhile, oil and natural gas consumption in China has increased rapidly in recent decades, which is accompanied with considerable fugitive emissions from the mining, processing, storage and transportation [30]. Additionally, fuel combustion is an important CH_4 emission source [31]. In rural China, straw and firewood are the two primary bio-fuels for daily cooking and domestic heating, incomplete combustion of biomass resources causes serious air pollution and releases a large amount of CH_4. All of these activities in energy fields lead to a large amount of CH_4 emissions.

To evaluate adequately the CH_4 emissions of various energy activities in China, specific efforts have been made to account for the emissions from coal mining [32–38], oil and natural gas system leakage [30], fuel combustion of social-economic sectors [39], and bio-fuel combustion in rural households [40–42]. There is clearly a growing body of studies about energy-related CH_4 emissions from notable sources in China, however, the estimations are based on the methods of different tiers and the data from distinctive and scattered sources.

There have also been several studies on the national-scale inventories of CH_4 emissions in some special years or as annual series in some early years, of which some deal with CH_4 emissions from energy activities in the country [24,43–47]. In particular, the issue of direct and indirect CH_4 emissions in China has been widely explored by Chen and his collaborators in a series of works for multi-scale systems input–output analysis of GHG emissions [24,48–52].

Nevertheless, there is still limited knowledge about the CH_4 emissions of energy activities in China. For instance, there are no systematic evaluations covering all the major sources and their specific contributions to the global climate change in a long period of time, especially reflecting the dramatic socio-economic changes since 2000. To understand the potential of emission mitigation and to identify mitigation measures for CH_4 emission reduction in China's energy fields, a quantification of the size and proportion of CH_4 emissions involved in China's energy activities and an assessment of the dynamics of the overall emissions are urgently required.

The purpose of this paper is twofold. First, a detailed estimation of energy-related CH_4 emissions in China during 1980–2007 is performed based on the most extensive, if not conclusive, and the most recent statistical data and research literatures available, covering all the major sources such as coal mining, oil and natural gas leakage, fossil fuel combustion, and bio-fuel combustion. Next, the roles of energy-related CH_4 emissions are systematically delineated in both the national and global GHG emission inventories.

The main context of this paper is organized as follows. In Section 2, the estimation methodology and data sources are described. Section 3 presents the estimates of CH_4 emissions from the main energy activities. In Section 4, the estimation results are organized systematically, and the budgets and inventory status of China's energy-related CH_4 emissions are analyzed. A comparison is made between the emission structures in China and in USA, and the uncertainty associated with the estimation is also discussed in this section. Finally, concluding remarks with policy making implications are made in Section 5.

2. Methodology and data sources

2.1. Coal mining

The CH_4 emissions from coal mining can be calculated as

$$E_{coal} = \sum_i P_i \times EF_i \times t - r \tag{1}$$

where E_{coal} is the CH_4 emissions from coal mining; P is the coal output; EF the emission factors of coal mining and post-mining (m^3 CH_4/t); t the gas coefficient (Gg CH_4/m^3); r the amount of CH_4 recovery; and i the category of coal mines.

There are two types of coal mines, underground coal mines and surface coal mines, with distinctive emission factors [26]. In China, over 95% of coal mines belong to underground coal mines [24,35]. Because of the great depth and high rank of China's coals, underground coal mines have higher CH_4 emissions than surface mines. Also, this special structure of coal mines results in more fugitive CH_4 emissions for the same amount of coal production in China than in developed countries. To calculate the fugitive emissions from underground coal mining, default emission factors provided

Table 1
Emission factors of coal mining in China (m^3/t).

Sources	Coal mining	Post-mining
Underground mining		
High-methane mines	21.83	3.02
Low-methane mines	4.53	1.13
Surface mining[a]	2.5	0.1

[a] Emission factors for surface mining are cited from IPCC default factors [26].

in IPCC [26] do not reflect the real situation in China appropriately [46]. In light of the coalbed methane concentration, underground coal mines can be further divided into high-methane coal mines and low-methane coal mines. On the basis of the Report of National Research on Climate Change of China, Zheng [33] provided the country-specific CH_4 emission factors for high-methane coal mine and low-methane coal mine in China, as listed in Table 1, which are adopted in this study.

Regarding the data of coal production in China, several authors have questioned the official Chinese energy statistics, especially in the year of 1996–2004 [53,54]. During this period, China′s coal output first declined and then rose precipitously, the unreported coal consumption in this period [55] would result in the underestimation of GHG emissions in China [54]. Fortunately, we notice that the Chinese statistical agencies have reduced the large data uncertainty in coal data in the recent years, and the updated data of China′s coal production during 1980–2007 examined in this study are available from China Statistical Yearbook [56], the most recently published statistical data. Since there are no official statistics for the outputs of China′s high-methane and low-methane coal mines, we resort to the study of Zheng et al. [34] for the estimation. According to this study, the outputs of Chinese high-methane mines accounted for 27% and 32% of the total coal production from underground mining in 1994 and 2000, respectively. As a preliminary approximation, the ratio of 30% for the coal output of Chinese high-methane mines in the total output from underground mining is adopted in the present study. The data of methane recovery in China are taken from Zhai et al. [57] and Lin et al. [58].

2.2. Oil and natural gas system leakage

According to the method recommended by IPCC [26], fugitive CH_4 emissions from oil and natural gas systems can be calculated as

$$E_{oil\&gas} = \sum_i P_i \times EF_i \quad (2)$$

where $E_{oil\&gas}$ is the fugitive CH_4 emissions from oil and natural gas systems; P is the activity level data of oil and natural gas systems (like oil well drill, oil production, oil refining, oil storage, oil transportation and oil sales; gas production, gas processing, gas transportation, and gas distribution); EF the emission factor; and i the activity category.

Based on the data availability and the calculation results for the year of 2006 by Liu et al. [30], the emission sources in oil and natural gas systems considered in this study include: crude oil production (onshore and fugitive emissions, venting, flaring), crude oil transportation (by pipelines, tanker or rail), and crude oil refining in oil systems; gas production (fugitive emissions, flaring), gas disposal (fugitive emissions, flaring), gas transportation (fugitive emissions, flaring), gas storage, and gas distribution in natural gas systems. Liu et al. [30] also provided the specific emission factors to calculate the CH_4 emissions from oil and natural gas systems in China on the basis of the local conditions and circumstances; their emission factors are adopted directly in this study, as presented in Table 2.

The data of crude oil output are mostly from the China Energy Statistical Yearbook [59–65]. The data of offshore crude oil production are provided by the China Marine Statistical Yearbook [66–68]. The data of oil refining are reported by BP [69]. Natural gas production and consumption data in China are also available from CESY [59–65].

2.3. Fuel combustion

It is known that fossil fuel combustion as the main source of CO_2 emissions also emits other GHGs such as CH_4. Though the CH_4 emission from fossil fuel combustion has not been included in the inventory compilation of previous studies [23,45,46], it is accounted for in the present study to reflect the actual situation of such emissions in China. The calculation of CH_4 emissions from fossil fuel combustion is based on the energy consumption data and the emission factors of various fuels associated with different processes. The energy consumption data are available from CESY [59–65] with the Energy Balance Sheets (in raw units) and Net Calorific Values of all energy sources. The procedure of data processing for energy-related emissions is adopted from Peters et al. [10]. Since the specific emission factors are not available, the default emission factors for fossil fuel combustion provided in IPCC [26] are adopted directly, as listed in Table 3.

The CH_4 emissions from the burning of straw and firewood in rural households can be estimated through

$$E_{bio-fuel} = B_{straw} \times EF_{straw} + B_{firewood} \times EF_{firewood} \quad (3)$$

where $E_{bio-fuel}$ is the CH_4 emissions from bio-fuel combustion; B_{straw} and $B_{firewood}$ are respectively the consumption amount of straw and firewood; EF_{straw} and $EF_{firewood}$ are the emission factors of straw and firewood combustion, respectively.

Zhang et al. [70] published a database regarding the emission factors of GHGs from rural household stoves in China, which have

Table 2
Emission factors of oil and natural gas system leakage.

Sources	Emission factor	Unit
Oil systems		
Oil production (onshore fugitive emissions)	3.00E−04	Gg/1000 m^3 oil production
Oil production (offshore fugitive emissions)	5.90E−07	Gg/1000 m^3 oil production
Oil production (venting)	8.55E−04	Gg/1000 m^3 oil production
Oil production (flaring)	2.95E−05	Gg/1000 m^3 oil production
Oil transportation by pipelines[a]	5.40E−06	Gg/1000 m^3 oil by pipeline
Oil transportation by tanker or rail[a]	2.50E−05	Gg/1000 m^3 oil by tanker
Oil refining	1.03E−05	Gg/1000 m^3 oil refined
Natural gas systems		
Gas production (fugitive emissions)	3.01E−03	Gg/MM m^3 gas production
Gas production (flaring)	8.80E−07	Gg/MM m^3 gas production
Gas disposal (fugitive emissions)	2.50E−04	Gg/MM m^3 gas production
Gas disposal (flaring)	2.40E−06	Gg/MM m^3 gas production
Gas transportation (fugitive emissions)	4.27E−04	Gg/MM m^3 gas marketable gas
Gas transportation (flaring)	1.80E−04	Gg/MM m^3 gas marketable gas
Gas storage	4.15E−05	Gg/MM m^3 gas marketable gas
Gas distribution	1.80E−03	Gg/MM m^3 gas utility sales

[a] We assume that all the domestic crude oil from onshore production was transported by pipelines; and all the crude oil from domestic offshore production and import was transported by tanker or rail.

Table 3
Default emission factors of fossil fuel combustion.

Category	Emission factor (kg/TJ)
Raw coal	1
Cleaned coal	1
Other washed coal	1
briquettes	1
Coke	1
Coke oven gas	1
Other gas	1
Other coking products	1
Crude oil	3
gasoline	3
kerosene	3
Diesel oil	3
Fuel oil	3
LPG	1
Refinery gas	1
Other petroleum products	3
Natural gas	1

Data sources: [26].

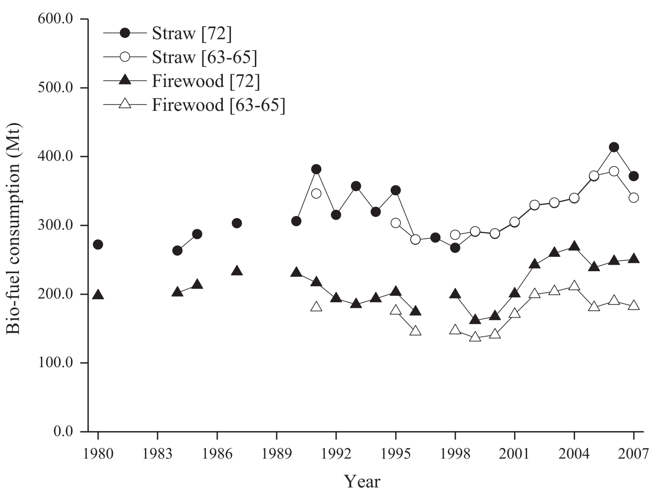

Fig. 1. Amount of straw and firewood combustion for energy purpose in China, 1980–2007.

been widely used to estimate the GHG emissions from rural energy consumption [40,41,71]. Therefore, the emission factors of straw and firewood fuel combustion in Zhang et al. [70], 4.56 g CH_4/kg straw and 2.7 kg CH_4/kg firewood, are adopted in this study.

Though a prerequisite for emission estimation, continuous time series data for firewood and straw consumption in rural China are difficult to be collected directly. CESY [63–65] provide the statistical data of rural non-commercial energy consumption covering straw and firewood for the years of 1991, 1995, 1996, 1998 and subsequent years. Based on the investigation regarding energy use in rural households performed by the Ministry of Agriculture, Zhang et al. [72] reported the rural energy consumption in China in terms of standard coal equivalent, and the time series data for straw and firewood consumption were provided with the exception of 1981, 1982, 1983, 1986, 1988, 1989, and 1997. With the help of the caloric values of straw and firewood provided in CESY [65], the energy consumption data of Zhang et al. [72] are converted into the data in raw units, as shown in Fig. 1. It is clear that the two sets of straw consumption data show little difference, while the firewood consumption data have significant discrepancy after 2002, but with a similar trend. To obtain a relatively comprehensive time series assessment and maintain data consistency, this work adopts the data in Zhang et al. [72] and generates the absent data through interpolation.

3. Results

3.1. Emissions from coal mining

With coal meeting nearly 70% of China's primary energy demand, China has the largest coal production in the world. The coal production in China during 1980–2007 is shown in Fig. 2. The coal output rose gradually from 1980 to 1996, and declined in 1997; however, it began to growing sharply since 2000. In 2007, the coal output in China amounted to 2.7 billion tons [56], 4.3 times of that in 1980. Owing to the special structure of coal mines in China dominated by the underground coal mining, large coal supply has resulted in a high growth rate of coalbed methane emissions.

The specific estimates for the CH_4 emissions in 2007 are listed in Table 4. Detailed results of CH_4 emissions from coal mining in China during 1980–2007 are listed in Table 5. China has been the world's leading emitter of coalbed methane [28]. In 2007, the CH_4 emission from coal mining totaled 18,825.5 Gg, 4.1, 2.4 and 1.8 times of those in 1980, 1990 and 2000, respectively. Underground mining of high-methane mines was the largest single emission source, followed by underground mining of low-methane mines, post-mining related with underground high-methane mines, and post-mining associated with underground low-methane mines. The CH_4 emissions from surface mining and surface post-mining amounted to only 234.5 Gg in 2007.

3.2. Emissions from oil and natural gas system leakage

The crude oil production in China during the period between 1980 and 2007 is displayed in Fig. 3. The crude oil output maintained steady growth in this period, with an average annual growth rate of 2.1%.

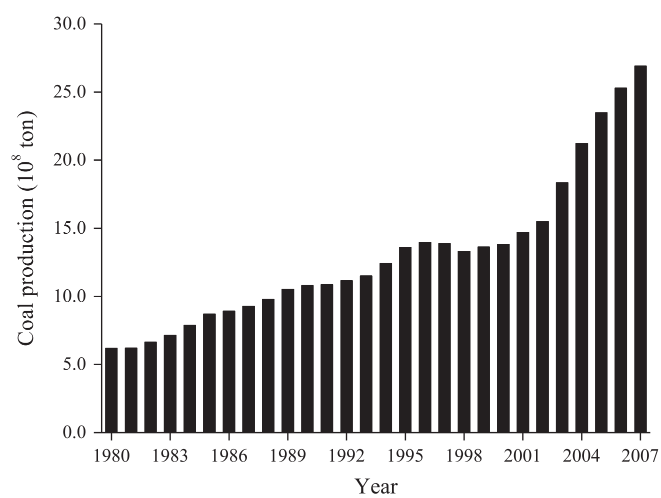

Fig. 2. Raw coal production in China, 1980–2007.

Table 4
Methane emissions from coal mining in China 2007.

Category	Coal mining	Post-mining	Total
Underground mining (10^8 t)	25.57	25.57	
High-methane mines	7.67	7.67	
Low-methane mines	17.9	17.9	
Surface mining (10^8 t)	1.35	1.35	
Emissions from underground mining (Gg)	16,654.8	2907.7	19,562.5
High-methane mines	11,221.4	1552.4	12,773.8
Low-methane mines	5,433.4	1355.3	6788.7
Emissions from surface mining (Gg)	225.5	9.0	234.5
Methane recovery (Gg)	971.5		971.5
Total emissions (Gg)	15,908.8	2916.7	18,825.5

Table 5
Methane emissions from coal mining in China, 1980–2007 (Gg).

Year	Underground high-CH_4 mines		Underground low-CH_4 mines		Surface mines		Recovery	Total
	Mining	Post-mining	Mining	Post-mining	Mining	Post-mining		
1980	2584.4	357.5	1251.4	312.2	51.9	2.1		4559.5
1981	2592.8	358.7	1255.4	313.2	52.1	2.1		4574.2
1982	2776.2	384.1	1344.2	335.3	55.8	2.2		4897.8
1983	2980.4	412.3	1443.1	360.0	59.9	2.4		5258.1
1984	3288.9	455.0	1592.5	397.2	66.1	2.6		5802.3
1985	3634.9	502.9	1760.0	439.0	73.0	2.9		6412.7
1986	3726.6	515.5	1804.4	450.1	74.9	3.0		6574.5
1987	3868.3	535.1	1873.0	467.2	77.7	3.1		6824.5
1988	4085.1	565.1	1978.0	493.4	82.1	3.3		7206.9
1989	4393.5	607.8	2127.3	530.7	88.3	3.5		7751.1
1990	4501.9	622.8	2179.8	543.7	90.5	3.6		7942.3
1991	4531.1	626.8	2193.9	547.3	91.0	3.6		7993.8
1992	4652.0	643.6	2252.5	561.9	93.5	3.7		8207.1
1993	4797.9	663.7	2323.1	579.5	96.4	3.9	231.8	8232.7
1994	5177.2	716.2	2506.8	625.3	104.0	4.2	268.0	8865.7
1995	5673.2	784.8	2747.0	685.2	114.0	4.6	297.5	9,711.3
1996	5823.3	805.6	2819.6	703.3	117.0	4.7	294.1	9,979.4
1997	5785.8	800.4	2801.5	698.8	116.2	4.6	293.5	9,913.9
1998	5552.4	768.1	2688.4	670.6	111.6	4.5	242.5	9,553.0
1999	5685.8	786.6	2753.0	686.7	114.2	4.6	300.0	9,730.9
2000	5769.1	798.1	2793.4	696.8	115.9	4.6	358.5	9,819.5
2001	6135.9	848.9	2971.0	741.1	123.3	4.9	361.8	10,463.3
2002	6461.1	893.8	3128.4	780.4	129.8	5.2	415.4	10,983.3
2003	7649.1	1058.2	3703.7	923.9	153.7	6.1	421.4	13,073.2
2004	8849.6	1224.3	4284.9	1068.9	177.8	7.1	404.0	15,208.6
2005	9795.8	1355.2	4743.1	1183.2	196.8	7.9	492.5	16,789.5
2006	10542.0	1458.4	5104.4	1273.3	211.8	8.5	609.7	17,988.6
2007	11221.4	1552.4	5433.4	1355.3	225.5	9.0	971.5	18,825.5

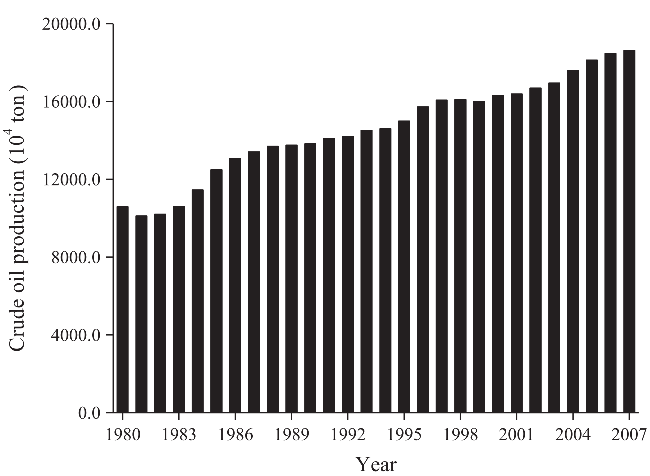

Fig. 3. Crude oil production in China, 1980–2007.

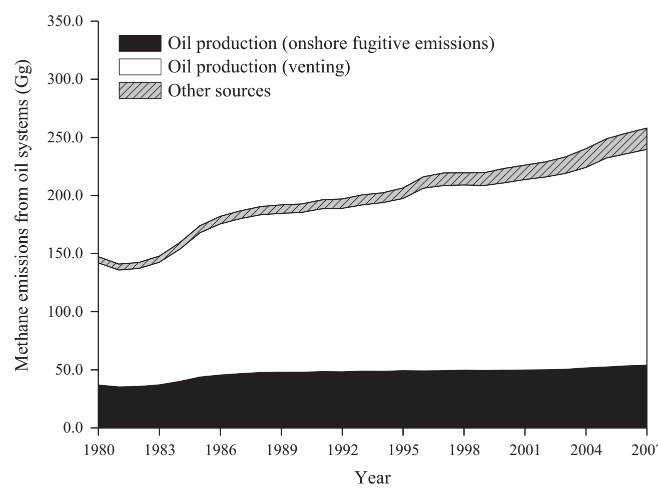

Fig. 4. Methane emissions from oil systems in China, 1980–2007.

In 2007, the total crude oil output in China amounted to 186.3 Mt, 1.8 times of that in 1980.

The fugitive CH_4 emissions from oil systems are shown in Fig. 4. In 2007, the fugitive CH_4 emission from oil systems in China totaled 258.1 Gg, 1.3 times of that in 1980, with an average annual growth rate of 1.7%. Oil system leakage in the crude oil production processes contributed the greatest to the CH_4 emissions. There are two main sources for the leakage, venting and onshore fugitive emissions—the former produced about 71.4–72.8% of the total emissions during 1980–2007; the latter more than 20%.

The outputs of natural gas in China during 1980–2007 are shown in Fig. 5. No substantial increase for the outputs of natural gas can be found between 1980 and 1995, with an increment of only 3.7 billion cubic meters. In contrast, the natural gas production has experienced a rapid growth since 1995. Moreover, the average annual growth rate of the natural gas output for the period between 2003 and 2007 reached 18.6%. The total output of natural gas amounted to 69.2 billion cubic meters in 2007, about 4.9, 4.5, and 2.5 times of those in 1980, 1990, and 2000, respectively.

The fugitive CH_4 emissions from natural gas systems in China during 1980–2007 are displayed in Fig. 6. Along with the sustaining increase of natural gas outputs, the fugitive emissions from the natural gas system also kept rising. The total CH_4 emission in 1980 was about 81.5 Gg while that in 1995 exceeded 100 Gg. From 1999 to 2007, the fugitive emissions from natural gas systems grew sharply, with an average annual growth rate of 15.9%. The total CH_4 emission from natural gas system leakage in 2007 is estimated to be 396.2 Gg, 4.9 times of that in 1980. As to the emission composition, natural gas production (fugitive emissions) was the largest emission source, contributing about 52.5–56.2% of the total emissions in the period, followed by natural gas distribution about

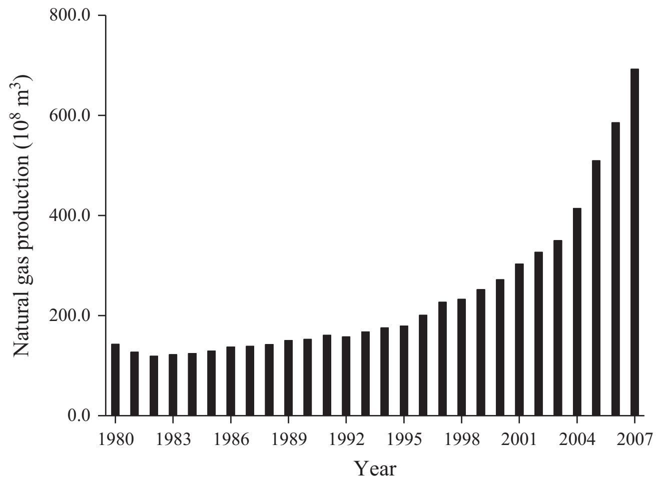

Fig. 5. Natural gas production in China, 1980–2007.

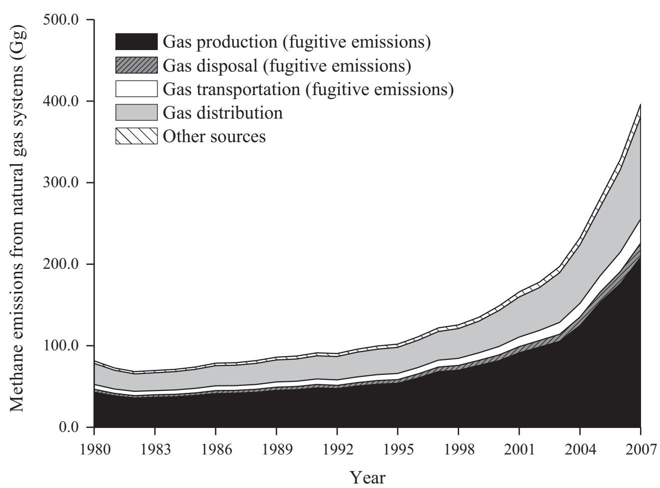

Fig. 6. Methane emissions from natural gas systems in China, 1980–2007.

Table 6
Methane emissions from fossil fuel combustion in typical years in China (Gg).

Category	1980	1985	1990	1995	2000	2005	2006	2007
Raw coal	10.8	14.8	18.0	22.9	21.4	34.5	37.7	40.5
Cleaned coal	0.0	0.0	0.2	0.3	0.3	0.5	0.5	0.6
Other washed coal	0.0	0.0	0.6	0.6	0.8	1.2	1.3	1.5
briquettes	0.0	0.0	0.0	0.0	0.1	0.2	0.2	0.2
Coke	1.2	1.3	1.9	2.8	2.8	6.4	7.5	8.2
Coke oven gas	0.2	0.2	0.3	0.3	0.4	0.8	0.9	0.9
Other gas	0.0	0.0	0.1	0.6	0.5	0.8	0.8	0.8
Other coking products	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1
Crude oil	1.7	1.2	1.0	0.6	1.1	1.2	1.3	1.3
gasoline	1.3	1.8	2.5	3.7	4.5	6.3	6.8	7.1
kerosene	0.5	0.5	0.5	0.7	1.1	1.3	1.4	1.6
Diesel oil	2.1	2.5	3.4	5.5	8.6	14.0	15.0	15.9
Fuel oil	3.8	3.5	4.2	4.6	4.9	5.3	5.0	5.1
LPG	0.1	0.1	0.1	0.4	0.7	1.0	1.1	1.1
Refinery gas	0.0	0.1	0.1	0.3	0.3	0.4	0.4	0.5
Other petroleum products	1.4	1.5	2.0	0.0	2.5	4.4	4.7	5.2
Natural gas	0.5	0.5	0.6	0.5	0.8	1.5	2.0	2.3
Total	23.6	28.0	35.4	44.1	50.8	79.7	86.6	93.0

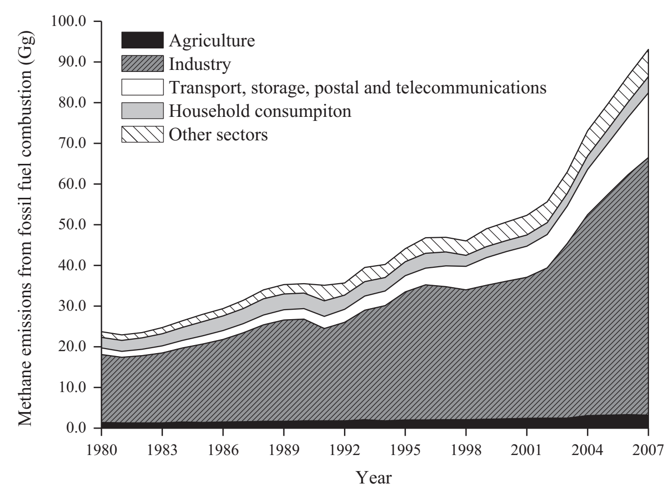

Fig. 7. Methane emissions from fossil fuel combustion in China, 1980–2007.

28.9–31.6% and transportation (fugitive emissions). Consequently, natural gas production (fugitive emissions) and natural gas distribution (fugitive emissions) determined the emission trend for natural gas systems in the whole period to a remarkable extent.

3.3. *Emissions from fuel combustion*

3.3.1. *Fossil fuel combustion*

Methane emissions from fossil fuel combustion by source in some typical years are listed in Table 6. The emissions from fossil fuel combustion rose rapidly from 23.6 Gg in 1980 to 93.0 Gg in 2007, corresponding to the continuous increase of energy consumption in China. The annual amount of CH_4 emissions from fossil fuel combustion was less than 100 Gg as a conservative estimation, of which raw coal combustion was the largest single emission source contributing over 40% of the total emissions. On the sectoral basis, industrial sector was the leading sector for CH_4 emissions, accounting for 64.7–71.4% of the total emissions during 1980–2007, as shown in Fig. 7.

3.3.2. *Bio-fuel combustion*

Fig. 8 shows the CH_4 emissions from straw and firewood combustion during 1980–2007. The total amount of CH_4 emissions from bio-fuel combustion in 2007 was 2370.3 Gg, 1.4 times of that in 1980. The major growth phase occurred in the period from 2000 to 2006. The amounts of CH_4 emissions from straw combustion were about 2–3 times of those from firewood combustion. For instance, the CH_4 emissions from straw combustion and firewood combustion in 2007 were 1694.5 Gg and 675.6 Gg, respectively. For the emission trend, methane emissions from firewood combustion show little variation while those from straw combustion show an increasing trend in recent years.

4. Discussion

4.1. *Total energy-related CH_4 emissions in China*

The composition data of energy-related CH_4 emissions by source in China covering the period of 1980 to 2007 are displayed in Fig. 9. In this period, the patterns of variation of energy-related CH_4 emissions can be described in terms of three phases, as follows: (a) from 1980 to 1995, the total CH_4 emissions rose rapidly from 6586.9 Gg in 1980 to 12,212.3 Gg in 1995, which corresponds to a 85.4% increase and an annual growth rate of 4.2%; (b) from 1996 to 2000, there were mild fluctuations over this period with the emissions around 12,000 Gg; (c) from 2001 to 2007, the average annual growth rate of the total emissions reached 9.1% and the total energy-related CH_4 emissions in 2007 amounted to 21,843.1 Gg, 3.3 times of those in 1980.

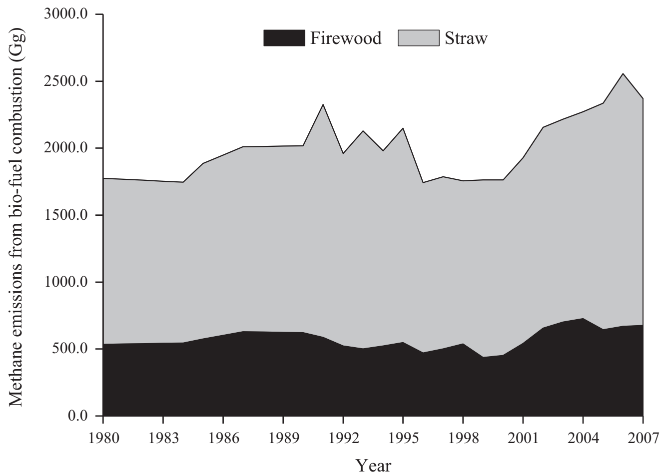

Fig. 8. Methane emissions from bio-fuel combustion in China, 1980–2007.

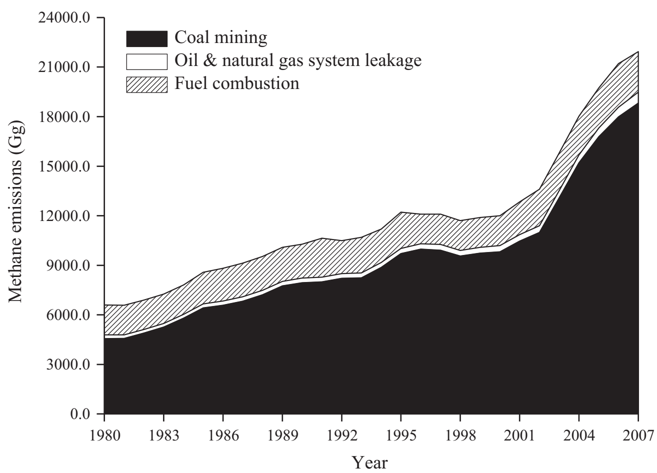

Fig. 9. Energy-related CH_4 emissions in China, 1980–2007.

The CH_4 emissions from coal mining were prominently more than those from other emission sources, which contributed 69.2% and 85.8% of the total emissions in 1980 and 2007, respectively. Fuel combustion was the second largest emission source, contributing a share of 11.2% and amounting to 2463.3 Gg in 2007. In addition, oil and natural gas systems also emitted 654.3 Gg CH_4 in 2007 (3.0%). In the past 28 years, 329.7 Tg CH_4 from energy activities was emitted, of which coal mining contributed 263.1 Tg, 79.8% of the total.

Two indicators of emission per capita and emission per GDP are employed below to characterize the energy-related CH_4 emission level in China. The energy-related CH_4 emissions per capita increased from 6.7 kg in 1980 to 16.6 kg in 2007 with an average annual growth rate of 3.5%. During the same period, the annual growth rate of the population was only 1.1%, much lower than that of the emissions. China's economy grew continuously by an average of 9.98% annually indicated by real GDP based on 1980 constant prices. Annual increase of the GDP was much higher than that of the emissions. As consequence, the energy-related CH_4 emissions per GDP declined continuously from 14.4 g/Yuan in 1980 to 3.7 g/Yuan in 2007 with an annual decrease rate of 4.8%.

4.2. Inventory status of energy-related CH_4 emissions in China

The contribution of CH_4 to total GHG emissions can be estimated by expressing the emission of CH_4 in CO_2-equivalent units through the indicator of Global Warming Potential (GWP) [20]. IPCC [20] recommended certain values for the GWPs of CH_4 over different time horizons. It follows that the total energy-related CH_4 emissions in 2007 were equivalent to 548.6 Mt CO_2-eq with the commonly referred lower IPCC GWP_{100} factor of 25 over a time horizon of 100 years and 1579.9 Mt CO_2-eq with the GWP_{20} factor of 72 over 20 years.

Recently, as an alternative way to quantify CO_2-equivalent, the global thermodynamic potential (GTP) indicator derived from global exergy analyses [73–77] has also been applied to evaluate GHG emissions [24,25,39,49,78–81]. The GTP represents the thermodynamic departure between the emission and its global environment. With the standard chemical exergy intensities of CH_4 and CO_2 as 51.98 kJ/g and 0.45 kJ/g respectively [76], the corresponding GTP factor of CH_4 is 115.51 relative to CO_2. Based on this GTP factor, the CH_4 emissions in 2007 corresponded to 2534.7 Mt CO_2-eq. Detailed results are displayed in Table 7.

Meanwhile, China's energy-related CO_2 emissions from fuel combustion increased from 1405.3 Mt in 1980 to 6027.9 Mt in 2007 [1], as listed in Table 7. Based on different equivalent indicators, the ratios of China's energy-related CH_4 emissions indicated by CO_2 equivalent to China's energy-related CO_2 emissions for the period between 1980 and 2007 are shown in Fig. 10. The annual growth rate of the energy-related CH_4 emissions in China was lower than that of the energy-related CO_2 emissions. It is worth noting that by the GTP, China's energy-related CH_4 emissions during 1980–2007 were equivalent to 42.0%–54.1% of China's energy-related CO_2 emissions, while even by the lower GWP_{100} up to 9.1%–11.7%. Prominently, the total CH_4 emissions in 2007 by the GWP_{100} were 548.6 Mt CO_2-eq, still greater than the nationwide gross anthropogenic CO_2 emissions (excluding

Table 7
Energy-related CH_4 emissions in China, 1980–2007.

Year	Emissions (Gg)	Emissions by GWP_{100} (Mt CO_2-eq)	Emissions by GWP_{20} (Mt CO_2-eq)	Emissions by GTP (Mt CO_2-eq)	Energy-related CO_2 emissions[a] (Mt)
1980	6,586.9	164.7	474.3	760.9	1,405.3
1981	6,578.8	164.5	473.7	759.9	1,391.4
1982	6,892.4	172.3	496.3	796.1	1,449.0
1983	7,253.9	181.3	522.3	837.9	1,521.4
1984	7,805.4	195.1	562.0	901.6	1,657.8
1985	8,573.8	214.3	617.3	990.4	1,704.5
1986	8,812.3	220.3	634.5	1,017.9	1,805.5
1987	9,132.4	228.3	657.5	1,054.9	1,941.7
1988	9,525.9	238.1	685.9	1,100.3	2,087.1
1989	10,079.6	252.0	725.7	1,164.3	2,166.7
1990	10,275.6	256.9	739.8	1,186.9	2,211.0
1991	10,642.8	266.1	766.3	1,229.4	2,324.7
1992	10,489.5	262.2	755.2	1,211.6	2,427.9
1993	10,696.6	267.4	770.2	1,235.6	2,627.0
1994	11,188.1	279.7	805.5	1,292.3	2,745.0
1995	12,212.3	305.3	879.3	1,410.6	2,985.9
1996	12,095.9	302.4	870.9	1,397.2	3,160.5
1997	12,089.2	302.2	870.4	1,396.4	3,100.6
1998	11,700.2	292.5	842.4	1,351.5	3,156.3
1999	11,897.5	297.4	856.6	1,374.3	3,046.4
2000	12,005.5	300.1	864.4	1,386.8	3,037.8
2001	12,836.1	320.9	924.2	1,482.7	3,084.0
2002	13,601.3	340.0	979.3	1,571.1	3,308.7
2003	15,782.4	394.6	1,136.3	1,823.0	3,829.7
2004	18,026.0	450.6	1,297.9	2,082.2	4,546.1
2005	19,735.3	493.4	1,420.9	2,279.6	5,058.3
2006	21,213.2	530.3	1,527.4	2,450.3	5,603.5
2007	21,943.1	548.6	1,579.9	2,534.7	6,027.9
Total	329,672.3	8241.8	23,736.4	38,080.4	79,411.7

[a] The data of CO_2 emissions from fuel combustion in China calculated by sectoral approach source from IEA [1].

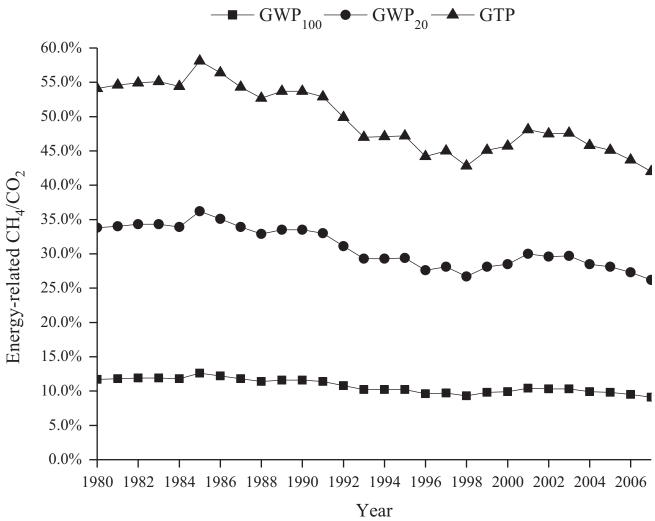

Fig. 10. Ratios of energy-related CH_4 emissions to CO_2 emissions in China, 1980–2007.

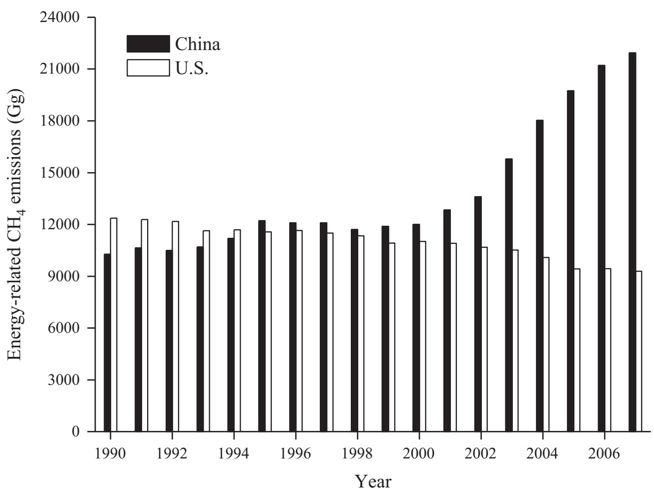

Fig. 11. Comparison for energy-related CH_4 emissions in China and the U.S.

emissions/removals from land use, land-use change, and forestry) in many developed countries such as UK (547.5 Mt), Italy (476.7 Mt), France (399.9 Mt), Australia (393.3 Mt), and Spain (367.8 Mt) in 2007 [82].

The accumulative emission of energy-related CH_4 in China for the nearly three decades from 1980 to 2007 was 329.7 Tg, corresponding to 8241.8, 23,736.4 and 38,080.4 Mt CO_2-eq by the GWP_{100}, GWP_{20} and GTP, and 10.4%, 29.9%, and 48.0% of the accumulative emission of energy-related CO_2 in China (79,411.7 Mt), respectively. China's energy-related CH_4 emissions by GTP are in magnitude of the same importance as China's energy-related CO_2 emissions. All these comparisons highlight the considerable contributions of China's energy-related CH_4 emissions to the national and even the global GHG emission inventories.

4.3. Comparison of energy-related CH_4 emissions in China and in USA

China and USA are the leading emitters of CH_4 in the world. Considering the same contributors, the total energy-related CH_4 emissions in USA decreased from 12,361 Gg in 1990 to 9289 Gg in 2007, corresponding to 42.5% and 35.5% of the total nationwide CH_4 emissions respectively, as reported in EPA [83]. As shown in Fig. 11, the energy-related CH_4 emissions in USA were greater than those in China before 1994, and then China surpassed USA gradually with an increasing emission gap in recent years. In 2007, China's CH_4 emissions from energy activities were 2.4 times those of USA. If we take demographic factors into account, the conclusion will be very different. USA had a total population of 303.82 million as of the end of 2007 and thus its energy-related CH_4 emission per capita was 32.7 kg in 2007, 2.0 times of that of China.

Displayed in Fig. 12 is a comparison of the emission shares for key source categories in China and in USA. As the main emission contributors in China, coal mining contributed 77.3% and 85.8% of the total energy-related CH_4 emissions respectively in 1980 and 2007, followed by fuel combustion. In contrast to the emission structure of China, natural gas system leakage was the top source in the US inventory, accounting for 51.0% of the total energy-related CH_4 emissions in 2007, followed by coal mining for 29.8% and oil system leakage for 14.8%. Meanwhile, the CH_4 emission from oil system leakage in China accounted for a very small proportion, which can be partly explained by the different energy structures between China and USA. It is worth noting that compared to the relatively steady structure of energy-related CH_4 emissions in USA during 1990–2007, drastic changes had occurred to the emission structure in China which are identified above.

4.4. Comparison with existing reports

The challenges of producing GHG emission inventories of the developing countries are about data availability and accuracy, the quantification of national specific emission factors, and the complexity of financial, institutional, political, organizational issues [84]. To reflect the actual status and progresses of inventory compilation and to identify related uncertainties, previous estimates about China's energy-related CH_4 emissions at a national scale are compared below with those presented in the present study.

The uncertainties of the emission estimation for coal mining have four possible sources. First, it is difficult to access the actual statistics of coal output from high-methane and low-methane coal mines in China. Based on the data of 1994 and 2000 in the work of Zheng et al. [34], this study employs the same proportional parameter for the time-series output data of both high-methane coal mines and low-methane coal mines for the period of 1980 to 2007. Second, the regional differences of emission factors are not taken into account. To estimate accurately the CH_4 emissions from coal mining, the CH_4 emission factors of different coal producing regions are needed, instead of the country-specific average emission factors adopted in this work. Third, there could be some discrepancies in the literature of the data of coalbed methane recovery and utilization in China reported by different scholars. Finally, data uncertainty in China's coal production statistics may also be significant but is difficult to quantify.

CCCCS [46] took into account the regional distribution of coalbed methane concentrations, and calculated the total CH_4 emission from coal mining in China as 8688.9 Gg in 1990. According to the State Administration of Coal Mine Safety, Chinese coal mine emitted 9.6 billion cubic meters or 6448.0 Gg CH_4 in 2000 [85]. Zhang and Wang [86] estimated that the total CH_4 emission from coal mining in China amounted to 6448.8 Gg in 2000 and underground mining of high-methane mines was the dominant emission source. However, EPA [47] estimated only 5598.8 Gg in 2000, which has been demonstrated to be too low. Yuan et al. [35] adopted the emission factors in Zheng [33], and estimated 12,184.1 Gg in 2002. Based on the report of the State Administration of Coal Mine Safety, Cheng et al. [87] reported the total CH_4 emission from underground coal mining in China, mainly from high-methane coal mines, was 13.8 Tg in 2007. A recent study performed by Zhang and Chen [24] reported the result of 19,410 Gg in 2007 by using the emission factors in Zheng [33] and an average theoretical recovery ratio of coalbed methane. Li and Hu [36] provided time series estimates of the CH_4

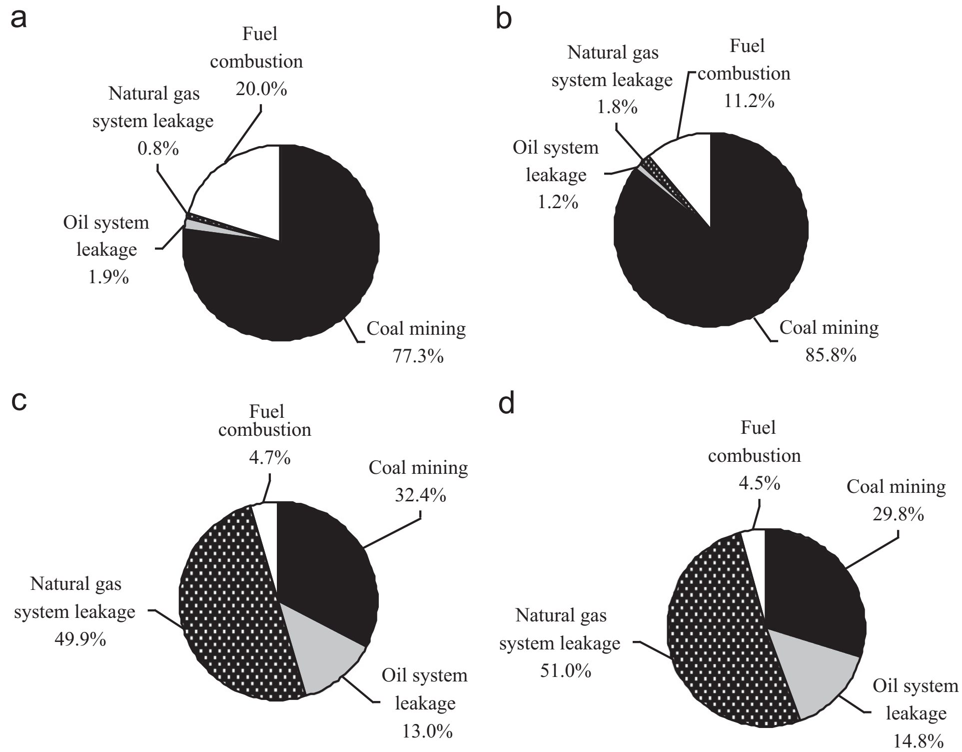

Fig. 12. Emission components of China and USA in 1990 and 2007. (a) China 1990, (b) China 2007, (c) USA 1990, (d) USA 2007.

emissions from underground coal mining in China through three specific parameters, average gas content per ton of coal (9.3 m^3/t), methane concentration (90.6%) and gas recovery rate (7%). Comparing these results with the present study (Table 5), our results are essentially consistent with those previous studies, considering statistical data discrepancy for the coal output [88], especially for the period between 1996 and 2004.

With regard to CH_4 emissions from oil and gas system leakage, there are only very limited studies at present. Uncertainty may arise due to the incomplete data and the inadequate evaluation of emission factors. For instance, it is difficult to obtain the actual data of oil wells and oil and gas fields in China, and the emissions from well drill, well testing and workover were excluded in the present study. Liu et al. [30] estimated that the fugitive emission from the workover (flaring and venting) in 2006 reached about 40 Gg.

CCCCS [46] estimated the total fugitive emission of oil and natural gas systems in China was 91.9 Gg in 1990, of which 49.4 Gg from oil systems and 42.4 Gg from natural gas systems. Zhang [45] and INCCCC [23] reported estimations of 101 Gg and 124 Gg in 1994, respectively, much lower than 202.3 Gg from the present study. Liu et al. [30] reported the total fugitive CH_4 emission in 2006 as 626 Gg, of which 371 Gg from oil systems and 255 Gg from natural gas systems, close to our results. Zhang and Chen [24] adopted the average emission factors of the year 1994 in INCCCC [23] directly and calculated the emissions as 258.3 Gg CH_4 in 2007 which underestimated the fugitive emission from oil and natural gas systems.

To estimate the emissions from fossil fuel combustion, uncertainty mainly comes from the selection of the default emission factors provided in IPCC [26]. Owing to a variety of reasons such as inadequate burning, the calculations based on the default emission factors may result in the underestimation of CH_4 emissions from China's energy consumption. Nevertheless, due to the low emission amount, the emissions from fossil fuel combustion can be ignored as done by most studies.

A few factors, such as ventilation conditions, type of combustion equipment, burning time, and biomass quality, will influence CH_4 emissions from bio-fuel combustion to a certain extent. As a consequence, there is the uncertainty of estimation from the adoption of a unified emission factor. By using the emission factors of 6.26 g CH_4/kg for straw combustion and 5.44 g CH_4/kg for firewood combustion, CCCCS [46] estimated that the emissions from bio-fuel combustion in 1990 were 2971.3 Gg, of which straw and firewood combustion contributed 1210.0 Gg and 1468.8 Gg, respectively, higher than our results. Cao et al. [89] adopted an Indian emission factor of 2.07 g CH_4/kg for firewood combustion (close to 2.7 g CH_4/kg in this study), and reported that the CH_4 emissions from firewood combustion amounted to 282.3 Gg in 2000. It is worthy of noting that some emission sources, such as manure burning, charcoal combustion, are excluded due to the data unavailability. CCCCS [46] estimated the CH_4 emissions from manure burning and charcoal combustion in 1990 amounted to 53.9 Gg and 234.4 Gg, respectively. In fact, owing to the energy structure transition, the amount of manure and charcoal used in rural households decreased rapidly in recent years, the current emissions are expected to be much lower than those in 1990.

In general, even considering such uncertainties in both methods and data, the scale and trend of the energy-related CH_4 emissions in China are unlikely to be affected significantly, and the results of the present study may offer fundamental information to the knowledge and understanding of the CH_4 emissions from energy activities in China since the great proportions of the emissions were contributed by coal mining, oil and gas system leakage, and fuel combustion which are considered. Also, we should emphasize that enhanced data monitoring and statistical analysis will be essential to prepare a more detailed national inventory.

5. Concluding remarks

Specific energy-related CH_4 emission inventories in China for the nearly three decades from 1980 to 2007 are presented,

covering all the remarkable emission sources of coal mining, oil and gas system leakage, fossil fuel combustion and bio-fuel combustion.

The total energy-related CH_4 emissions in China are estimated rising from 6586.9 Gg in 1980 to 21,843.1 Gg in 2007, with an average annual increase of 4.7%. The emission per capita increased from 6.7 kg in 1980 to 16.6 kg in 2007 with an average annual growth rate of 3.5%. The emission per GDP declined continuously from 14.4 g/Yuan in 1980 to 3.7 g/Yuan in 2007 (1980 constant prices), with an annual decrease of 4.8%.

As to the emission structure, the CH_4 emission from coal mining was notably more than those from other emission sources, which increased from 4559.5 Gg (69.2% of the total) in 1980 to 18,825.5 Gg (85.8%) in 2007 with an average annual increase of 5.5%. The emission from fuel combustion was dominated by those from bio-fuel, which fluctuated between the periods of 1980–2007 and amounted to 2463.3 Gg in 2007. Meanwhile the emission from oil and natural gas system leakage remained relatively low, but increased sharply from 228.7 Gg in 1980 to 654.3 Gg in 2007, with an average annual increase of 3.7%. In general, the energy-related CH_4 emission structures in China are determined by the rapidly uprising emissions from coal mining, quite different from those of USA characterized by the dominated fugitive emissions from natural gas and oil systems with relatively steady shares.

China′s energy-related CH_4 emissions play an essential role in the GHG emission inventories of both China and the world. China′s energy-related CH_4 emissions during 1980–2007 were equivalent to 42.0–54.1% of China′s energy-related CO_2 emissions, by the Global Thermodynamic Potential (GWP) factor of 115.51. Even by the commonly referred lower IPCC Global Warming Potential (GWP) factor of 25, they are up to 9.1–11.7% of the CO_2 emissions and 548.6 Mt-eq CO_2 in 2007, which is larger than the nation-wide gross CO_2 emissions in many developed countries such as UK. The accumulative emission of energy-related CH_4 in China for the period between 1980 and 2007 amounted to 329.7 Tg, corresponding to 38,080.4 Mt CO_2-eq and 48.0% of the total accumulative emission of energy-related CO_2 in China by the GTP. China and the United States are the leading emitters of CH_4 in the world, the energy-related CH_4 emissions in USA were greater than those in China before 1994, and then China surpassed USA gradually with an increasing emission gap in recent years. Though the emission per capita in China was 1/2 of that in USA, China released energy-related CH_4 emissions 2.4 times of USA in 2007. All these comparisons highlight the essential importance of China′s energy-related CH_4 emissions in the national and even the global GHG emission inventories.

Given the rapid increase in energy consumption especially coal consumption (up to 3.52 billion tons in 2011) to fuel its economy engine, China will have uprising energy-related CH_4 emission in the future. The current pattern of energy-related CH_4 emissions implies the tremendous reduction potential in China′s energy fields. Since CH_4 emissions growth in China is largely affected by coal mining, reasonable exploitation of coal resources and effective utilization of coalbed methane represent a cost-effective means to reduce significantly the CH_4 emissions, which will also contribute to alternative renewable energy development, emission reduction of air pollutants, and local economic benefit. Though the CH_4 emissions from other sources are much less than those from coal mining in China, the mitigation potential is still great. Energy policies and technological options for emission reduction from oil and natural gas system leakage and bio-fuel combustion can also make significant strides toward CH_4 emission mitigation in the long term. Furthermore, the direct emissions from production on site and the relationships of energy use with economic growth both need to be analyzed before undertaking an exercise in emission mitigation for the future. The consumption-side control on CH_4 emissions can also play an essential role, owing to indirect CH_4 emissions induced by the excessive construction activities, inefficiency in production and consumption of energy and resources, extensive capital investment, and export-oriented trade by the Chinese economy.

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References

[1] IEA. CO_2 emissions from fuel combustion 2009–highlights; 2009, ⟨http://www.iea.org/co2highlights/co2highlights.pdf⟩.
[2] Rong F. Understanding developing country stances on post-2012 climate change negotiations: comparative analysis of Brazil, China, India, Mexico, and South Africa. Energy Policy 2010;38(8):4582–91.
[3] Zhang ZX. Is it fair to treat China as a Christmas tree to hang everybody′s complaints? Putting its own energy saving into perspective Energy Economics 2010;32(Suppl. 1):S47–56.
[4] Stern DI, Jotzo F. How ambitious are China and India′s emissions intensity targets? Energy Policy 2010;38(11):6776–83.
[5] Xinhua net. China announces targets on carbon emission cuts; 2009, ⟨http://news.xinhuanet.com/english/2009-11/26/content_12544181.htm⟩.
[6] Jiang B, Sun Z, Liu M. China′s energy development strategy under the low-carbon economy. Energy 2010;35(11):4257–64.
[7] Zhang ZX. China in the transition to a low-carbon economy. Energy Policy 2010;38(11):6638–53.
[8] Chen GQ, Zhang B, Greenhouse gas emissions in China 2007. Inventories and input–output analysis. Energy Policy 2010;38(10):6180–93.
[9] Tao J, Yu S, Wu T. Review of China′s bioethanol development and a case study of fuel supply, demand and distribution of bioethanol expansion by national application of E10. Biomass & Bioenergy 2011;35(9):3810–29.
[10] Peters GP, Weber CL, Liu JR. Construction of Chinese energy and emissions inventory, Industrial ecology programme reports and working papers; 2006, ⟨http://www.ntnu.no/eksternweb/ multimedia/archive/00023/rap port4_06 web_23578a.pdf⟩.
[11] Wei YM, Liu LC, Fan Y, Wu G. China energy report 2008: carbon emissions research. Beijing: Science Press; 2008 (in Chinese).
[12] Zhang M, Mu H, Ning Y. Accounting for energy–related CO_2 emission in China, 1991–2006. Energy Policy 2009;37(3):767–73.
[13] He J, Deng J, Su M. CO_2 emission from China′s energy sector and strategy for its control. Energy 2010;35(11):4494–8.
[14] Lin B, Sun C. Evaluating carbon dioxide emissions in international trade of China. Energy Policy 2010;38(1):613–21.
[15] Zhang Y, Zhang J, Yang ZF, Li SS. Regional differences in the factors that influence China′s energy-related carbon emissions, and potential mitigation strategies. Energy Policy 2011;39(12):7712–8.
[16] Geng Y, Tian M, Zhu Q, Zhang J, Peng C. Quantification of provincial-level carbon emissions from energy consumption in China. Renewable & Sustainable Energy Reviews 2011;15(8):3658–68.
[17] Guo XD, Zhu L, Fan Y, Xie BC. Evaluation of potential reductions in carbon emissions in Chinese provinces based on environmental DEA. Energy Policy 2011;39(5):2352–60.
[18] Yi WJ, Zou LL, Guo J, Wang K, Wei YM. How can China reach its CO_2 intensity reduction targets by 2020? A regional allocation based on equity and development Energy Policy 2011;39(5):2407–15.
[19] IPCC. IPCC fourth assessment report: climate change; 2007 (AR4); 2007, ⟨http://www.ipcc.ch/publications_and_data/publications_and_data_reports.htm⟩.
[20] Bousquet P, Ciais P, Miller JB, Dlugokencky EJ, Hauglustaine DA, Prigent C, Van der Werf GR, Peylin P, Brunke EG, Carouge C, Langenfelds RL, Lathière J, Papa F, Ramonet M, Schmidt M, Steele LP, Tyler SC, White J. Contribution of anthropogenic and natural sources to atmospheric methane variability. Nature 2006;443:439–43.
[21] West JJ, Fiore AM, Horowitz LW, Mauzerall DL. Global health benefits of mitigating ozone pollution with methane emission controls. Proceedings of the National Academy of Sciences of the United States of America 2006;103(11):3988–93.

[22] Yusuf RO, Noor ZZ, Abba A, Hassan MAA, Din MFM. Methane emission by sectors: a comprehensive review of emission sources and mitigation methods. Renewable & Sustainable Energy Reviews 2012;16(7):5059–70.
[23] INCCCC. Initial National Communication on Climate Change of China; 2004, ⟨http://www.ccchina.gov.cn/file/en_source/da/da2004110901.pdf⟩.
[24] Zhang B, Chen GQ. Methane emissions by Chinese economy: inventory and embodiment analysis. Energy Policy 2010;38(8):4304–16.
[25] Zhang B, Peng S, Xu X, Wang L. Embodiment analysis for greenhouse gas emissions by Chinese economy based on Global Thermodynamic Potentials. Energies 2011;4(11):1897–915.
[26] IPCC. The 2006 IPCC guidelines for national greenhouse gas inventories (2006 Guidelines); 2006.
[27] Yu H, Zhou G, Fan W, Ye J. Predicted CO_2 enhanced coalbed methane recovery and CO_2 sequestration in China. International Journal of Coal Geology 2007;71 (2–3):345–57.
[28] IEA. Coal mine methane in China: a budding asset with the potential to bloom; 2009, ⟨http://www.iea.org/papers/2009/china_cmm_report.pdf⟩.
[29] Luo D, Dai Y. Economic evaluation of coalbed methane production in China. Energy Policy 2009;37(10):3883–9.
[30] Liu JR, Yao J, Gallaher M, Coburn J, Fernandez R. Study on methane emission reduction potential in China′s oil and natural gas industry; 2008, ⟨http://www.epa.gov/gasstar/documents/chinese/techreport_methanestudy.pdf⟩.
[31] Bhattacharya SC, Abdul Salam P, Sharma M. Emissions from biomass energy use in some selected Asian countries. Energy 2000;25(2):169–88.
[32] Bibler CJ, Marshall JS, Pilcher RC. Status of worldwide coal mine methane emissions and use. International Journal of Coal Geology 1998;35(1–4):283–310.
[33] Zheng S. Coalbed methane emissions inventory in China. China Coal 2002;28 (5):37–40 (in Chinese).
[34] Zheng S, Wang Y, Wang Z. Amount of methane exhausting to atmosphere in coal mines of China. Safety in Coal Mines 2005;36(2):29–33 (in Chinese).
[35] Yuan BR, Nie ZR, Di XH, Zuo TY. Life cycle inventories of fossil fuels in China (I): energy sources consumption and direct pollutant emissions. Modern Chemical Industry 2006;26(3):59–64 (in Chinese).
[36] Li HJ, Hu YH. Preliminary evaluation on the contribution of CMM to greenhouse gas emissions in China. China Coalbed Methane 2008;5(2):15–7 (in Chinese).
[37] Yang M. Climate change and energy policies, coal and coal mine methane in China. Energy Policy 2009;37(8):2858–69.
[38] Su S, Han J, Wu J, Li H, Worrall R, Guo H, Sun X, Liu W. Fugitive coal mine methane emissions at five mining areas in China. Atmospheric Environment 2011;45(13):2220–32.
[39] Ji X, Chen GQ. Unified account of gas pollutants and greenhouse gas emissions: Chinese transportation 1978–2004. Communications in Nonlinear Science and Numerical Simulation 2010;15(9):2710–22.
[40] Edwards RD, Smith KR, Zhang J, Ma Y. Models to predict emissions of health-damaging pollutants and global warming contributions of residential fuel/stove combinations in China. Chemosphere 2003;50(2):201–15.
[41] Yan X, Ohara T, Akimoto H. Bottom-up estimate of biomass burning in mainland China. Atmospheric Environment 2006;40(27):5262–73.
[42] Wang S, Wei W, Du L, Li G, Hao J. Characteristics of gaseous pollutants from biofuel-stoves in rural China. Atmospheric Environment 2009;43(27): 4148–54.
[43] Khalil MAK, Shearer MJ, Rasmussen RA. Methane sources in China: historical and current emissions. Chemosphere 1993;26(1–4):127–42.
[44] Wang MX, Dai AG, Huang J, Ren LX, Shen RX. Sources of methane in China: rice fields, agricultural waste treatment, cattle, coal mines, and other minor sources. Scientia Atmospherica Sinica 1993;17(1):52–64 (in Chinese).
[45] Zhang R, Wang M, Li J, Yang X, Wang X. The present status of the emission methane in China. Climatic and Environmental Research 1999;4(2):194–202 (in Chinese).
[46] CCCCS. China climate change country study. Beijing: Tsinghua University Press; 2000 (in Chinese).
[47] EPA. EPA Report 430-R-06-003: global anthropogenic non-CO_2 greenhouse gas emissions: 1990–2020; 2006, ⟨http://www.epa.gov/climatechange/economics/downloads/GlobalAnthroEmissionsReport.pdf⟩.
[48] Zhou JB. Embodied ecological elements accounting of national economy. PhD dissertation. Beijing: Peking University; 2008 (in Chinese).
[49] Chen GQ, Chen ZM, Carbon emissions and resources use by Chinese economy 2007. A 135-sector inventory and input–output embodiment. Communications in Nonlinear Science and Numerical Simulation 2010;15(11):2647–732.
[50] Chen ZM, Chen GQ, Zhou JB, Jiang MM, Chen B. Ecological input–output modeling for embodied resources and emissions in Chinese economy 2005. Communications in Nonlinear Science and Numerical Simulation 2010;15 (7):1942–65.
[51] Zhou SY, Chen H, Li SC. Resources use and greenhouse gas emissions in urban economy: ecological input–output modeling for Beijing 2002. Communications in Nonlinear Science and Numerical Simulation 2010;15(10):3201–31.
[52] Chen GQ, Chen ZM. Greenhouse gas emissions and natural resources use by the world economy: ecological input–output modeling. Ecological Modelling 2011;222(14):2362–76.
[53] Peters GP, Weber CL, Guan D, Hubacek K. China′s growing CO_2 emissions—a race between lifestyle changes and efficiency gains. Environmental Science & Technology 2007;41(17):5939–44.
[54] Weber CL, Peters GP, Guan D, Hubacek K. The contribution of Chinese exports to climate change. Energy Policy 2008;36(9):3572–7.
[55] Akimoto H, Ohara T, Kurokawa J, Horii N. Verification of energy consumption in China during 1996–2003 by using satellite observational data. Atmospheric Environment 2006;40(40):7663–7.
[56] CSY. China Statistical Yearbook; 2010, ⟨http://www.stats.gov.cn/tjsj/ndsj/2010/indexch.htm⟩.
[57] Zhai C, Lin BQ, Wang L. The status and problems of underground CMM drainage and utilization in China. Natural Gas Industry 2008;28(7):23–6 (in Chinese).
[58] Lin XF, Liu XF, Liu S, Di ZQ. Summarize of China coal-bed methane utilization. Coal Technology 2010;29(4):1–3 (in Chinese).
[59] CESY. China Energy Statistical Yearbook 1986. Beijing: China Statistical Publishing House; 1987 (in Chinese).
[60] CESY. China Energy Statistical Yearbook 1989. Beijing: China Statistical Publishing House; 1990 (in Chinese).
[61] CESY. China Energy Statistical Yearbook 1990. Beijing: China Statistical Publishing House; 1991 (in Chinese).
[62] CESY. China Energy Statistical Yearbook 1991–1996. Beijing: China Statistical Publishing House; 1998 (in Chinese).
[63] CESY. China Energy Statistical Yearbook 1997–1999. Beijing: China Statistical Publishing House; 2001 (in Chinese).
[64] CESY. China Energy Statistical Yearbook 2000–2002. Beijing: China Statistical Publishing House; 2004 (in Chinese).
[65] CESY. China Energy Statistical Yearbook 2004–2008. Beijing: China Statistical Publishing House; 2005–2009 (in Chinese).
[66] CMSY. China Marine Statistical Yearbook 1993. Beijing: China Ocean Press; 1994 (in Chinese).
[67] CMSY. China Marine Statistical Yearbook 1998. Beijing: China Ocean Press; 1999 (in Chinese).
[68] CMSY. China Marine Statistical Yearbook 2000–2008. Beijing: China Ocean Press; 2001–2009 (in Chinese).
[69] BP. Statistical review of world energy full report 2011; 2011, ⟨http://www.bp.com/assets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/spreadsheets/statistical_review_of_world_energy_full_report_2011.xls⟩.
[70] Zhang J, Smith KR, Ma Y, Ye S, Jiang F, Qi W, Liu P, Khalil MAK, Rasmussen RA, Thorneloe SA. Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors. Atmospheric Environment 2000;34(26):4537–49.
[71] Liu Y, Kuang Y, Huang N, Wu Z, Xu L. Popularizing household-scale biogas digesters for rural sustainable energy development and greenhouse gas mitigation. Renewable Energy 2008;33(9):2027–35.
[72] Zhang LX, Yang ZF, Chen B, Chen GQ. Rural energy in China: pattern and policy. Renewable Energy 2009;34(12):2813–23.
[73] Wall G. Exergy–a useful concept. PhD dissertation. Göteborg: Chalmers University of Technology; 1986.
[74] Chen GQ. Exergy consumption of the earth. Ecological Modelling 2005;184(2–4):363–80.
[75] Chen GQ. Scarcity of exergy and ecological evaluation based on embodied exergy. Communications in Nonlinear Science and Numerical Simulation 2006;11(4):531–52.
[76] Szargut J. Exergy method: technical and ecological applications. Southampton: WIT Press; 2005.
[77] Hermann WA. Quantifying global exergy resources. Energy 2006;31(12): 1685–702.
[78] Cai ZF. Water resources and greenhouse gas emissions covered ecological exergy account. PhD dissertation. Beijing: Peking University; 2009 (in Chinese).
[79] Gasparatos A, Ei-Haram M, Horner M. A longitudinal analysis of the UK transport sector, 1970–2010. Energy Policy 2009;37(2):623–32.
[80] Ji X, Chen GQ, Chen B, Jiang MM. Exergy–based assessment for waste gas emissions from Chinese transportation. Energy Policy 2009;37(6):2231–40.
[81] Zhang B, Chen GQ. Physical sustainability assessment for the China society: exergy-based systems account for resources use and environmental emissions. Renewable & Sustainable Energy Reviews 2010;14(6):1527–45.
[82] UNFCCC. National greenhouse gas inventory data for the period 1990.2007; 2009, ⟨http://unfccc.int/resource/docs/2009/sbi/eng/12.pdf⟩.
[83] EPA. Inventory of U.S. greenhouse gas emissions and sinks: 1990–2008 (EPA 430-R-10-006); 2010, ⟨http://epa.gov/climatechange/emissions/downloads10/US-GHG-Inventory-2010_Report.pdf⟩.
[84] Friedrich E, Trois C. Greenhouse gases accounting and reporting for waste management—a South African perspective. Waste Management 2010;30 (11):2347–53.
[85] Jiang K, Hu X. Emission scenario of non–CO_2 gases from energy activities and other sources in China. Science in China. Series C: Life Sciences) 2005;48 (Suppl. 2):955–64.
[86] Zhang WS, Wang Y. Promoting coalbed methane utilization in China with Clean Development Mechanism. Venture Capital 2006;7:28–30 (in Chinese).
[87] Cheng Y, Wang L, Zhang X. Environmental impact of coal mine methane emissions and responding strategies in China. International Journal of Greenhouse Gas Control 2011;5(1):157–66.
[88] Streets DG, Jiang K, Hu X, Sinton JE, Zhang XQ, Xu D, Jacobson MZ, Hansen JE. Recent reductions in China′s greenhouse gas emissions. Science 2001;294 (5548):1835–7.
[89] Cao GL, Zhang XZ, Wang D. Inventory of atmospheric pollutants discharged from biomass burning in China continent. China Environmental Science 2005;25(4):389–93 (in Chinese).